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EXPEDIENT SHELTERING IN PLACE: AN EVALUATION FOR THE CHEMICAL STOCKPILE EMERGENCY PREPAREDNESS PROGRAM

William K. Blewett
Dennis W. Reeves
Victor J. Arca
David P. Fatkin
Brenda D. Cannon

RESEARCH AND TECHNOLOGY DIRECTORATE

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This study examines the protective capacity of sheltering in place, a means of protecting the public if an accidental release of hazardous chemicals occurs. The report consists of two parts. The first is a review of the literature regarding the theory, practical parameters, and procedures for sheltering in place, including an analysis of sheltering instructions published by 11 organizations/communities. The second part presents results of tracer-gas experiments conducted on 12 buildings to determine the effect of expedient sealing measures upon the protection that can be provided by sheltering in place. Results of the experiments show that expedient sealing measures applied to a selected safe room substantially reduce air exchange rates. In using a bathroom with window as a safe room, placing a rolled wet towel at the base of the door and taping vents produced a 16.5% mean reduction in air exchange rate. Applied to a windowless bathroom or walk-in closet, this measures yielded a mean reduction of 30 to 32%. When tape was placed around the door and a sheet of plastic was taped over the window of a bathroom, the mean reduction was 34.3%.

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EXECUTIVE SUMMARY

This study examines the protective capacity of sheltering in place, a means of protecting the public if an accidental release of hazardous chemicals occurs. The first part of this report is a review of the literature regarding the theory, practical parameters, and published procedures for sheltering in place. The second part presents results of 36 experiments conducted on 12 buildings at Aberdeen Proving Ground, MD to determine the effect of expedient sealing measures upon the protection provided by sheltering in place.

Sheltering in place involves going/remaining indoors; closing all windows, vents, and doors; and turning off heating, ventilating, and air conditioning (HVAC) systems before the cloud of hazardous chemicals arrives. A tightly closed building will not keep out contaminated air completely but will allow it in slowly. After the hazard has passed, the closed building likewise retards the release of contaminants that have infiltrated; therefore, the occupants attain maximum protection by vacating the building or increasing its air exchange rate (opening windows and doors) immediately upon passage of the hazardous cloud.

Taping doorways and vents, placing plastic sheeting over windows, and laying a wet towel at the base of each door are additional measures that constitute what is called expedient sheltering. Applying permanent sealing measures, such as those used to weatherize homes, is referred to as enhanced sheltering. A fourth level of sheltering, pressurized sheltering, provides the greatest amount of protection but involves relatively large costs. Pressurized shelters are not known to have been used to protect the public in any chemical accidents.

Several studies have concluded that normal/expedient sheltering in place is a practical and effective means of protecting the public against transient chemical hazards. Sheltering's effectiveness has been demonstrated by successful application in actual emergencies. Sheltering procedures have been published and implemented by several U.S. communities in which industrial chemicals are stored or processed. Because of its application in industrial accidents, normal/ expedient sheltering in place has been identified under the Chemical Stockpile Emergency Preparedness Program as an option for the emergency response plans of communities near chemical agent stockpile sites and their future demilitarization facilities.

The principal advantage of sheltering is that it can be implemented more rapidly than evacuation. Its principal disadvantage is that the physical protection it affords is quite variable--sensitive to the duration of exposure, the tightness of the building in which shelter is sought, the timing of implementation, and the rates at which the materials in the building absorb and desorb the hazardous chemicals, as explained below:

- Protection decreases as the duration of the building's exposure to the hazardous cloud increases.

- The tightness of the building, stated in terms of its air exchange rate, is the most important variable for determining protection. This rate varies greatly among buildings and for a given building over time. It increases with wind velocity and with the

inside-outside temperature difference. It increases when heating, ventilating, and air conditioning systems are in use, and it can vary between upstairs and downstairs, from room to room, and from season to season.

● The rates at which materials in the buildings absorb and desorb a chemical as it passes through cracks and pores and comes in contact with materials inside the building affects the protection. There are, however, very little data available with which to accurately estimate this effect, which is referred to as filtering. Neglecting this factor provides a conservative estimate of protection.

● The timing of implementation strongly affects protection. Once the cloud passes, the closed building slowly releases the contaminants that have entered, so that beyond the point of passage, being inside presents a greater hazard than being outside. Protection factor, defined as the dosage outside divided by the dosage inside, approaches a value of 1 (zero protection) as the values for time of exposure and time of occupancy grow large--if there is no absorption or filtering of the agent. How rapidly this protection factor approaches 1 is determined by the tightness of the building and the ambient conditions. To illustrate this, if a building of 0.5 air changes per hour is exposed to a hazardous cloud for 15 minutes, it has a protection factor of 17 if the occupants exit immediately upon cloud passage. If they wait an additional 30 minutes to exit, however, the protection factor drops to 3.7.

Expedient sheltering is based upon an assumption that techniques can be applied rapidly, with little or no training, and with common household items to reduce substantially the air exchange rate of a room or building--and consequently to increase the protection. Applying room selection criteria and expedient sealing techniques to the room of the building best suited for sheltering may also reduce the variability of air exchange rate among shelters, thus narrowing the range of protection that can be achieved within a community.

In a review of 11 published instructions for sheltering in place, this study found that most sheltering instructions specified neither expedient sealing measures nor room selection criteria. The instructions also do not address what energy conservation studies have identified as a major leakage area, the wall-to-floor junction behind baseboards. Sealing such an area is considered a part of enhanced sheltering procedures rather than expedient sheltering.

To determine the effectiveness of two levels of expedient sealing measures in reducing the air exchange rates of rooms, 36 tracer gas experiments were conducted on 10 residential buildings and two mobile office trailers at Aberdeen Proving Ground, MD. Although these buildings are not considered representative of the broad range of buildings that could be employed for sheltering under the CSEPP, the results demonstrate that the expedient sealing measures do substantially reduce air exchange rates.

Applying the simpler of the two methods (placing a wet, rolled towel at the base of the door and taping any vents) to a bathroom with a window produced a 16.5% mean reduction in air exchange rate. Applied to a windowless bathroom or walk-in closet, this method yielded a mean reduction of 30 to 32%.

Applying a more extensive method--taping around the door and taping a sheet of plastic over the window--to a bathroom containing a window produced a mean reduction of 34.3%.

In the weather conditions that existed during tests of the 12 buildings, the calculated protection factors ranged from 15 to 68 for normal sheltering against a 10-minute hazardous exposure. Against a 1-hour exposure, the protection factors ranged from 3 to 13. With the best expedient room sealing measures, the calculated protection factors increased to a range of 39 to 101 for 10-minute exposure and to 7 to 17 for 1-hour exposure. These illustrations neglect any filtering effect and assume perfect implementation.

Although expedient sealing measures on selected rooms produced lower air exchange rates, there was greater variability in the rates among the sealed rooms than among the houses. This indicates that further gains in protection can be achieved by improving the sealing methods and/or sealing other leakage paths such as the wall-to-floor junction in the selected safe room.

This study identified a type of recirculating indoor air purifier with a carbon filter medium as having potential to improve the protection achievable through expedient sheltering. Such filter units, which are now widely available to consumers, are recommended for further evaluation.

A set of recommended procedures for expedient sheltering in place were developed during this study.

The following are the recommendations of this study:

- Develop estimates of the probable duration of an accidental release from a chemical agent demilitarization or storage facility. The most likely range of exposure duration must be defined to determine the specific applicability of sheltering to the CSEPP.

- Quantify the filtering effect. There are no data available on the rates of absorption of the chemical agents upon building materials, rates which are specific to each agent and the material to which it is exposed. Neglecting this effect yields low estimates of protection but also results in underestimating the period needed to purge the building after exposure.

- Test and evaluate the use of a consumer type indoor air purifier (recirculation filter containing carbon filter elements) to increase the protection afforded by sheltering in a selected room.

- Evaluate the combination of both enhanced sheltering measures (permanent sealing of areas such as the wall-to-floor junction) and expedient measures to reduce the air exchange rate of a selected safe room.

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PREFACE

The work described in this report was funded by the Chemical Stockpile Emergency Preparedness Program. The work was begun in March 1995 and completed in November 1995.

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EXPEDIENT SHELTERING IN PLACE: AN EVALUATION FOR THE CHEMICAL STOCKPILE EMERGENCY PREPAREDNESS PROGRAM

1. INTRODUCTION.

Sheltering in place is a means of protecting the public when there is an accidental release of hazardous chemicals, whether from a storage site, transport vehicle, or manufacturing facility for industrial chemicals. Originally developed as a protective action for nuclear accidents, sheltering in place has been employed in chemical accidents of varying severity since about 1985. It is considered an alternative to evacuation, the standard response in such emergencies.

To shelter in place, a person goes indoors or remains indoors; closes all windows, vents, and doors; and turns off heating, ventilating, and air conditioning (HVAC) systems before the cloud of hazardous chemicals arrives. A tightly closed building will not keep out the contaminated air completely but will allow it in very slowly. After the cloud passes, the closed building will very slowly release any contaminated air that has entered. Thus, the final step of the sheltering procedure is to open all windows and vacate the building as soon as the hazard has passed.

The amount of protection afforded by sheltering in place varies mainly with the tightness of the building and the duration of the hazardous exposure. Protection is greatest when shelter is sought in a tightly constructed building and when the hazardous exposure is brief. Protection decreases as the duration of the hazardous plume increases.

If there is adequate forewarning, additional measures such as sealing windows and doors with tape and plastic sheeting can be employed to further reduce the rate at which contaminated air infiltrates. Based upon the extent of such sealing measures, four levels of sheltering have been defined by the Oak Ridge National Laboratory (ORNL) in a study for the Chemical Stockpile Emergency Preparedness Program (CSEPP).[1]

- **Normal Sheltering** involves closing all windows and doors and turning off all HVAC equipment.

- **Expedient Sheltering** involves simple, rapid measures in addition to those of normal sheltering: placing a rolled wet towel at the base of the door(s); taping over ventilation ducts, electrical outlets or other openings; taping around doors; or taping plastic sheeting over windows.

- **Enhanced Sheltering** involves measures to reduce infiltration beforehand: caulking joints, applying weather strips and storm windows, or making other modifications to reduce infiltration, similar to those typically applied in weatherizing homes. These measures may be employed in combination with expedient measures.

- **Pressurized Sheltering** involves the use of special gas-particulate filter-blower unit(s) to pressurize a tightly sealed room, building, or portable enclosure with filtered air.

The filter-blower produces an outward flow (exfiltration) of clean air through leakage points, preventing the infiltration of contaminated air.

Pressurized sheltering provides the highest level of protection but involves relatively high costs. Pressurized shelters are not known to have been employed to protect the public in any chemical accident. Normal and expedient sheltering have been used in virtually all instances of sheltering in place.

Because it has been effective in industrial chemical accidents, normal/ expedient sheltering in place has been identified under the CSEPP as an option for the emergency response plans of communities near chemical agent stockpile sites and their future demilitarization facilities. Chemical agent munitions are currently in storage awaiting demilitarization at eight military installations in the continental U.S.--Aberdeen Proving Ground, MD; Anniston Army Depot, AL; Lexington-Blue Grass Army Depot, KY; Newport Army Ammunition Plant, IN; Pine Bluff Arsenal, AR; Pueblo Depot Activity, CO; Tooele Army Depot, UT; and Umatilla Depot Activity, OR.

The level of protection attainable through normal sheltering in place can be estimated if the building's air exchange rate--the rate at which inside air is exchanged with outside air is known. There is a large amount of data on the air exchange rates of various types of buildings as a result of studies on energy conservation and indoor air quality. There are very little data, however, on the effects expedient sealing measures have upon air exchange rates.

2. PURPOSE

This study was conducted to determine the state of knowledge on sheltering in place, to examine its potential as a protective action in an accidental release from a chemical weapons storage/demilitarization facility, to determine the improvement expedient sealing measures have upon protection, and to produce a recommended recipe card for sheltering.

3. BACKGROUND

3.1 Sheltering in Place as an Alternative to Evacuation.

Evacuation has long been the standard approach for protecting citizens when a chemical accident occurs. Over the last decade, however, sheltering in place has become recognized and accepted as a practical and effective alternative to evacuation. Its use has increased greatly since 1988, when a conference on in-place protection for chemical emergencies was held at Emmittsburg, MD to define the methods, requirements, and benefits of sheltering in place.[2] Since then, several local emergency planning committees (LEPC) have instituted programs for sheltering in place and have published instructions for sheltering in their communities.

One advantage of sheltering in place is that the protective action can be completed with less warning time than is needed for evacuation. Although evacuation is theoretically the safer alternative, it is not always so in practice. The amount of forewarning is the key in determining which is the safer alternative for a specific incident. To draw an analogy from weather emergencies: Evacuation is always preferred in the event of a hurricane because the public can be warned well in advance, and the path and extent of the storm can be well predicted. Sheltering in place, however, is usually the only effective response for a tornado because warning times are typically short and the storm's path is unpredictable.

In chemical accidents, warning times can be very short, particularly when compared to the time needed to complete an evacuation. Evacuation routes can also lead through areas into which the hazardous plume already has travelled or is predicted to travel. There are several considerations in deciding whether sheltering or evacuation is the safer alternative in a specific situation. These are described in a 1988 report by the National Institute of Chemical Studies.[3] The approach of some LEPCs, however, has been to consider sheltering in place as the first option, because it takes less time than evacuation. Thus, authorities initiate sheltering while deciding whether to order an evacuation.

3.2 Factors Influencing the Protection Provided by Sheltering in Place.

Factors that determine the level of protection can be divided into two categories: physical factors and implementation factors. The former determine the theoretical or maximum physical protection achievable in a specific building. The latter, which involve behavioral influences, determine the practical capability of sheltering. This report focuses upon the physical factors.

3.2.1 Physical Factors.

The amount of physical protection a building can provide, that is, the protection achievable when implementation is 100% efficient, is determined by the:

- Air exchange rate of the building at the time of hazardous exposure
- Duration of the exposure and the time occupants remain in the building after the hazardous cloud has passed.
- Filtering that occurs as the contaminated air enters the building

Protection is normally stated in terms of protection factor, the ratio of the dosage outside to the dosage inside a protective enclosure. Dosage is concentration integrated over time; when the concentration is constant, dosage is equal to the concentration multiplied by the time of exposure. Dosage is usually stated in terms of mg-min/m^3.

Protection can also be stated in terms of a dose reduction factor, which is the inverse of protection factor.

$$\text{Protection Factor} = \frac{\text{Outdoor Dosage}}{\text{Indoor Dosage}} = \frac{1}{\text{Dose Reduction Factor}}$$

Once the protection factor of a building is known for specific conditions, the dosage in which sheltering can be safely applied can be determined by multiplying the protection factor by the dosage at which physiological effects are known to occur for each specific chemical agent.

3.2.1.1 **The Air Exchange Rate of the Building.**

A building employed as a chemical shelter can be likened to a leaky boat. It can be used for short excursions but should not be left in the water for long periods. The safety of its use is governed by the rate of its leaks in relation to its volume and the length of time it is to be in the water. Although the ventilation of a building is more complex, the protection a building provides against airborne hazards is similarly determined: by the rate of air leakage relative to its volume and the length of time the building is in the chemical cloud.

All buildings, even those tightly constructed, have air leakage. This is commonly expressed in terms of the air exchange rate, the rate of uncontrolled exchange of air between the indoors and outdoors through cracks, pores, or other openings connecting the living area with the outdoor environment. This rate is stated relative to the volume of the building as the number of air changes per hour (ACH).

The air exchange rate determines how rapidly airborne contaminants infiltrate the building from the outside and how rapidly they are purged from the building once the outside air is no longer contaminated. If the building's air exchange rate remains constant, it will take longer to purge the contaminant after the cloud has passed than it took for the contaminant to enter the building, and at some point during or after cloud passage, the concentration inside will exceed the concentration outside.

The equation for protection factor of an enclosure that has air leakage (an air exchange rate greater than zero) is found in several references; reports by Englemann[4], and Lewis[5] are three that explain its derivation. In this equation, shown below, protection factor is a function of three variables: R is the air exchange rate of the building in ACH. T is the time the building is exposed to the hazardous cloud, in hours; and t is the time of occupancy, in hours, beginning upon the arrival of the hazardous cloud.

$$\text{Protection Factor} = \frac{RT}{RT + e^{-Rt} - e^{R(T-t)}}$$

There are two different time variables because there are two distinct phases of the process. The first phase (time T) is when the cloud envelopes the building, during which the interior concentration increases. The second phase (time t - T) is after the cloud passes, during which the interior concentration decreases as contaminants that have entered are released from the building.

The protection factor is highest when T equals t, that is, when the occupancy time is equal to the time the hazardous cloud is present around the building. In this case, the occupants exit as soon as the cloud passes, and the third term in the equation becomes equal to 1. As the value of t grows large, the second and third terms approach zero, and the protection factor approaches 1. This means that the dosage to which occupants are exposed inside will eventually equal the dosage accumulated outside if they do not, after cloud passage, exit into clean air or increase the air exchange rate by opening windows and doors.

To illustrate the effects of exposure time (T) and occupancy time (t) upon protection factor, the equation above was used to calculate the protection factor of a building having an air exchange rate of 0.5 ACH. These calculated protection factors, shown in Table 1, illustrate the importance of taking steps to vacate or aerate the building immediately after cloud passage. With an exposure time of 15 minutes, a protection factor of 16.7 is achieved with immediate exiting; that is, the occupants are exposed to about 1/17th the hazardous dosage they would have been exposed to in remaining outside. When the occupants wait an additional 30 minutes before vacating the building, however, the protection factor decreases markedly; the exposure dosage is about four times greater.

Table 1. Illustration of Protection Factors Calculated for a Building of 0.5 ACH as the Exposure and Occupancy Times Vary.

Time Building is Exposed (T)	Time of Occupancy, From Cloud Arrival (t)	Protection Factor
15 min.	15 min.*	16.7
15 min.	45 min.	3.7
1 hr	1 hr*	4.7
1 hr	1½ hr	2.6
2 hr	2 hr*	2.7
2 hr	2½ hr	2.0

*In the three examples marked by an asterisk, occupants vacate the building as soon as the cloud passes; that is, T and t are equal. In the other three examples, the occupants wait one half hour before exiting. Note: This example neglects the effect of filtering, absorption of the chemical vapor by the building, which would increase protection factors.

Chemical warfare experiments conducted in 1948-49 demonstrated that the dosage inside a building approaches the dosage outside if there is no substantial loss of agent as a result of absorption by materials in the building. In exposing a building (of air exchange rate 1 ACH) to a smoke cloud for durations of 15 to 30 seconds, the dosage accumulated inside the building over a one-hour period ranged from 50 to 80% of the outside dosage, even though the inside concentration was only 1/100th of the outside concentration.

The effect upon concentration has also been examined in Canadian studies.[6] A closed building dampens the rapid fluctuations in concentration caused by the random variability inherent in atmospheric diffusion, protecting the occupants from exposure to high peak concentrations. This effect is significant in protecting against agents for which the concentration, rather than the cumulative dosage, determines the physiological effects. For the chemical warfare agents of the CSEPP, however, the effects are a function of dosage, rather than maximum concentration.

The protection factor equation above is based upon the assumption that as long as the chemical cloud is present, its concentration is constant. Other assumptions in its application are that the building and all its leakage areas are uniformly exposed; that the air is well mixed inside the building; and that there is no filtering effect. These assumptions, particularly with regard to absence of filtering, result in a conservative estimate of protection; that is, the equation gives a *lower* protection factor than would actually occur.

3.2.1.2 **Filtering Effect.**

Filtering occurs when the chemical vapor/gas is absorbed or deposited as it passes through cracks and pores while entering the building or as it comes in contact with materials inside the building--particularly porous materials such as draperies, carpets, and other fabrics. The effect of filtering has been examined in at least four studies on sheltering (by Birenzvige[7], Stearman[8], Engelmann[4] and Christy and Chester[9]), and it has been shown to increase the protection factor.

Filtering is neglected in most estimates of protection afforded by sheltering in place because there are very little data on the rates of absorption and desorption of chemical vapors/gases and because filtering is less important than the air exchange rate in determining the amount of protection. Rates of absorption and desorption are specific to each combination of chemical agent and the material by which it is absorbed. Only one study is known to have quantified the rates at which a fabric absorbs and desorbs chemical warfare agents; it examined such rates for the U.S. Army battledress uniform exposed to soman and mustard vapors.[10]

To estimate the effect filtering has upon the protection a building provides, one must apply estimates of several variables: the rate at which the agent vapor is absorbed by the materials of the building (stated as deposition velocity), the rate at which it desorbs, the surface area of the paths (cracks and pores) through which it enters the building, and the surface area inside the building.

Using deposition velocity estimates ranging from 0.01 to 0.1 cm/second, Birenzvige[7] calculated that for a three-hour exposure, absorption would reduce the dosage to which occupants of a 1 ACH building are exposed by 35% if the deposition rate is 0.01 and by 85% if the deposition rate is 0.1. These estimates, however, are based upon a desorption rate of zero; that is, it is assumed the agent would be retained indefinitely. Such is not likely to be the case, however, as a portion of what is absorbed will eventually desorb. Thus, the effect of desorption is to introduce a lag time and consequently to decrease the dosage to which occupants are exposed before they vacate the building.

3.2.1.3 **Variability in Air Exchange Rates.**

Air exchange rates vary widely, not only from building to building but also for a given building over time. The protection afforded by sheltering in place therefore is also highly variable.

"The natural variability of construction causes modern houses in both Canada and the U.S.A. to vary in leakiness by about a factor of two above and below the mean value," notes Dr. D.J. Wilson of the University of Alberta, who has done extensive research on sheltering in place. "These results indicate that the protection afforded by sheltering indoors will be highly variable within a neighborhood of houses exposed to a toxic release."[11]

Various studies on energy conservation and indoor air quality have produced a large source of data on air exchange rates of U.S. buildings, and these provide an estimate of the range of exchange rates that can be expected. One study published in 1987 showed the range for low-income houses and modern houses to be about 0.2 to 5 ACH during the heating season, with a median rate of approximately 0.7 ACH.[12]

The natural air exchange rate is *not* a constant value for each building, however. It can change continually with a number of variables, some of which are controlled by the basic procedures of sheltering:

- **Wind velocity and direction.** The air exchange rate increases as wind velocity increases. Wind produces a pressure difference between the outside and inside, causing air to infiltrate through the windward wall and exfiltrate through the leeward wall. This flow results from both the positive pressure difference on the windward side and the negative pressure created by wake effects and flow separation on the leeward side. The wind direction with respect to the location of leakage points--windows, vents, cracks, and other openings--is also significant in determining the rate of air exchange.

- **Inside-outside temperature difference.** As the temperature difference between inside and outside increases, the air exchange rate increases. Differences in mean indoor and outdoor temperatures, whether positive or negative, lead to different pressure distributions with height on the indoor and outdoor faces of the walls. These differences impose a pressure difference across cracks, pores, or openings that connect the indoor and outdoor environments. This is referred to the stack effect or buoyancy driven component.

- **HVAC systems.** If any HVAC ductwork is located external to the living area (in attics, garages, or crawl spaces) it can be a major pathway for infiltration, and the air exchange through such ducts increases when the central HVAC blower is operating. A study of 31 homes in Tennessee found that the rate of air exchange nearly doubled when the central blower was operating: The mean value was 0.78 ACH with the blower on and 0.44 ACH with the blower off.[13] In a study of mobile homes, this difference was even greater: 2.3 to 2.7 ACH with the blower on and 0.8 ACH with it off.[14]

- **Combustion.** With the exception of mobile homes, most U.S. residential buildings heated by combustion (by oil, natural gas, wood, or coal) have furnaces or stoves that draw combustion air from the living area. The combustion process induces a flow of air from the outside, through the living area, and out the chimney.

- **Seasonal variations.** Air exchange rates are highest in winter and the lowest in summer as a result of contraction and expansion of building materials as moisture content changes with relative humidity. A study of homes in the U.K. found this seasonal variation to be on the order of 40% for some houses.[15] One study of American houses found rates about 22% lower in the summer than in the winter.[16] A second study on two U.S. houses found the difference to be about 20%,[17] and a third found air exchange rates four times greater in winter than in summer.[18]

- **Upstairs/downstairs.** Air exchange rates can be substantially higher downstairs than upstairs. A study of two houses over a one-year period, found the rates to range from 0.07 to 0.32 ACH upstairs, and 0.14 to 1.69 ACH downstairs.[18] Downstairs rates were from 4 to 7 times higher than upstairs rates in one house that had not been weatherized. The study also found that when measurements were made with the HVAC blower turned off to minimize airflow among zones of the house, the air exchange rate downstairs was about 0.1 ACH higher than upstairs. The high downstairs rates during winter were consistent with the expected upward airflows due to inside-outside temperature differences. Other studies suggest that the downstairs air exchange rate is more closely related to the temperature difference, and the upstairs rate is more closely related to wind speed; the upstairs typically has a greater exposed perimeter wall area with windows and other potential leakage sites.

- **Room variations.** Variation in air exchange rate among rooms results from differences in building design, construction practices, orientation with respect to the wind, and location with respect to perimeter walls. The number of windows, doors, and vents in a room, and the configuration of each are important. One analysis suggests that a room without windows or doors might have a rate of 0.5 ACH, one with a door or window on one side would have a rate of 1 ACH; on two sides, 1.5 ACH; and three sides, 2 ACH.[3]

- **Method of measurement.** Values for air exchange rate vary not only with the conditions and building configuration at the time of measurement, but also with the method of measurement. Two different methods are commonly used, as defined in standards of the American Society for Testing and Materials:* fan pressurization and tracer gas dilution. With the former, air leakage is determined at a given internal pressure. The latter, which involves releasing a tracer gas inside the building and measuring the rate at which its concentration decreases, determines the natural air exchange rate at the conditions existing at the time of measurement. Measurements by this method can vary over a range of 5 to 1 for a single house, depending upon the weather conditions.[19] There is no simple formula for relating the data obtained by the two different methods. The pressurization method applies pressure equally to all walls and surfaces, while the forces due to wind or temperature differences are asymmetrical. One rule of thumb is that the rate under natural conditions is approximately 1/20th the airflow rate (in ACH) needed to pressurize the building to 50 Pascals. This roughly predicts only a single infiltration rate independent of wind and temperature differences.

It is standard practice to have the central HVAC fan operating (for air mixing) when taking measurements by the tracer gas dilution method. As noted above, this can substantially increase the rate of air exchange. Thus, most data acquired by this method may not accurately reflect the exchange rate of building as it would be when used for sheltering.

In studying the effectiveness of sheltering against a radiological hazard, Engelmann[4] developed estimates of air exchange rates that could be expected for residential buildings under conditions approximately those of sheltering. By selecting only data that had been acquired with furnace and fans off and with no occupant activity (such as opening and

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*ASTM E779, "Standard Test Method for Determining Air Leakage Rate by Fan Pressurization" and ASTM E741, "Standard Test Methods for Determining Air Change in a Single Zone by Means of Tracer Gas Dilution", American Society of Testing and Materials, 1916 Race St., Philadelphia, PA, 19103.

closing doors), he developed graphs of air exchange rates as a function of wind speed and indoor-outdoor temperature difference. These show an apparent minimum exchange of 0.1 ACH for tight houses and 0.3 ACH for leaky houses. Although his analysis indicates that air exchange in the leakier houses configured for sheltering would be significantly less than that indicated by the larger body data on exchange rate, it is based upon too few data for conclusions about the full range of protection expected in sheltering.

The effect of wind and inside-outside temperature differences are simpler to account for than the effect of HVAC operation. Several models have been developed for determining the effects of wind and temperature differences.[19] However, it is important to note that the effect of wind is also to reduce the concentration of a chemical cloud, to disperse it, and to cause its more rapid passage. For example, modeling has shown that at 10 mi/hr wind speed, the dosage and maximum concentration at a point directly downwind of a mustard artillery burst are about 5 to 10% of the values that occur at ½ mi/hr.[20]

3.2.2 **Measures to Reduce the Air Exchange Rate.**

How much can the sealing measures normally applied in weatherization of buildings be expected to reduce the air exchange rate? Data regarding this provide an indication of reductions that are possible with *enhanced* sheltering, for comparison to those of expedient sheltering.

A study of Canadian homes found that applying weatherstripping and caulking in the following ways produced a median reduction in air leakage of 31% for conventional houses: weatherstripping exterior doors and windows; caulking exterior doors, windows, electrical plugs and switches on exterior walls, ceiling lights, and electrical openings in the attic, plumbing stacks, vents, and ducts passing through attics, fireplace and furnace chimneys in the attic, cracks along interior partitions, the attic hatch, cracks between concrete walls and subfloor, floor joist area, perimeter of mail/coal chutes, general cracks and openings in walls.[21]

In testing two matched homes, it was shown that air exchange rates could be lowered 22% in summer and 24% in fall with the following measures: Applying sill plate sealer and caulking between masonry and frame wall; adding a vapor barrier in the upper level floor overhang and on the inside foundation/knee wall; sealing electrical outlets and switch boxes; sealing pipe and cable penetrations through wall top plates; caulking windows; adjusting exterior doors; weatherstripping the attic access panel; adjusting garage doors; sealing the wood stove insert plate and mouldings; and adjusting exhaust fan dampers.[22]

With regard to the vapor barrier, Wilson[11] concluded: "The most important factor that influences leakage area is whether a house has an air-vapor barrier in the walls and ceiling. As a rough estimate, houses built in cold climates after 1960 usually have vapor barrier, while older houses do not."

In examining the cost of such sealing measures, a study published in 1988 by Chester[23] estimated that to reduce the whole house air exchange rate from 1 ACH to

0.25 ACH would cost approximately $1,000 per house (1988 dollars). To apply sealing measures to just one room of the house, the estimate was $200.

3.2.2.1 Expedient Sealing Measures.

The procedures of expedient sheltering are based upon an assumption that there are techniques that can be applied rapidly, with little or no training, and with common household items to significantly reduce the air exchange rate of a room or building.

It is postulated that by applying room selection criteria and expedient sealing techniques to one room of the building best suited for sheltering, not only can a higher protection factor can be achieved but also the variability of protection--that is, the variability of air exchange rate from building to building--can be reduced. A practical advantage of applying sealing measures to a single room is that they can accomplished more rapidly and simply than if they are applied to the whole house.

There is little data on the effectiveness of expedient methods of room sealing. In evaluating methods of emergency protection against aerosols, ORNL found that a room sealed with polyethylene sheeting and tape provided a protection factor at least 10 times greater than the house as a whole when challenged with spores of *Bacillus globegii*.[9]

The ORNL study also examined the effectiveness of expedient sealing measures in experiments conducted on 13 dwellings in East Tennessee in 1989 using the tracer gas dilution method.[1] Three experiments were conducted in each house to measure in sequence the air exchange rate of the whole house, the rate of the selected room sealed by wet towel under the door, and rate of the same room sealed by tape and plastic sheeting. Although this approach of taking the three measurements sequentially was subject to uncontrolled temporal variations in the air exchange rate, it showed that when the doors, windows, plumbing, and electrical fixtures were taped, the exchange rate of the room was on the average only 45.6% of the air exchange rate of the room sealed with only a wet towel at the base of the door.

The ORNL study also yielded time and habitability data. To tape and seal the selected room took from 2.3 to 38.6 minutes with an average of 15.7 minutes. Simply closing the doors and windows of the house and turning off the HVAC, which are the steps of normal sheltering, took 3.2 minutes on the average.

Results of these trials showed habitability of the sealed rooms to be of some concern. During the experiments, which were run in the months of June and July, the temperature in the sealed room rose an average of about 2°F and the relative humidity rose by about 12%, on average, over the sheltering period of 40 minutes, and the occupants became uncomfortably hot.

3.2.3 Implementation.

Implementation factors--behavioral and technical influences unrelated to the protective capability of the building used for sheltering--are important in determining the protection achieved by sheltering in place. These are discussed only briefly here, as they are covered in detail in several documents on protective actions.[1,2,3,24] To implement sheltering in place requires the capability to:

- Ensure the residents know how to take the protective action
- Determine rapidly that a release has occurred
- Determine the areas that may be affected by the release
- Communicate a timely warning to all people in the affected areas
- Communicate the appropriate time to vacate in-place shelters

Only the fifth of these capabilities is specific to sheltering in place. The others listed above must be a part of the emergency response system whether the protective action is evacuation, sheltering in place, or use of individual protective equipment. The importance of the fifth capability--communicating to the community that the hazard has passed--can be seen in the protection factor estimates of Table 1. In the case of an evacuation, the all-clear notice can be delayed to ensure the hazard has abated; delaying the return of the evacuees to their homes increases the margin of safety. In the case of sheltering, however, delaying the all-clear signal for residents sheltering in place beyond the actual moment that the hazard has passed *decreases* the safety of those sheltering. Delays in issuing the instructions for sheltering--whether to initiate the action or to vacate shelters--decrease the effectiveness of sheltering. If a person receives some exposure before getting into a shelter and remains in the shelter long after cloud passage, it is possible to receive a greater dosage than might have been received without sheltering.

3.3 Current Procedures for Sheltering in Place.

In a 1989 literature review, the ORNL found eight instances in which sheltering in place had been implemented for protection against a chemical release.[1] Some of these can be described as passive applications; that is, the chemical release occurred when residents in the affected area were indoors with windows and doors already closed (such as on a winter night), so the decision to shelter in place required no action by the residents.

There has been no subsequent survey to compile a current list of applications of sheltering; however, presentations at the September 1995 Conference on Protecting the Public[24] in Charleston, WV, indicate that the number has grown markedly. Contra Costa County, California, for example, has employed sheltering in place seven times in five years, including a July 1993 accident involving the release of 12,000 gallons of oleum (presentation by Tracey Hein-Silva, Contra Costa County Health Department, Sept 21, 1995). As a result of this release, 22,000 people sought medical attention at hospitals and 22 were hospitalized; however, 100 employees who sheltered in place for more than three hours 3,000 ft directly downwind of the release showed no effects of the chemical. Sheltering in place is also known to have been employed, though without actual exposure of chemical agents, to protect Israeli citizens from the threat of missile-delivered chemical agents during the Persian Gulf War in 1990-91.

Instructions for sheltering in place have been published and distributed by several communities where hazardous industrial chemicals are stored or processed. One organization, the NICS, has made available a sheltering kit, which includes sealing materials and an instructional videotape.

Instructions for sheltering in place published by the following communities or organizations were reviewed during this study.

- National Institute for Chemical Studies: video tape and technical report
- American Red Cross: brochure
- Michigan Department of State Police: pamphlet
- Deer Park, TX: information on community calendar
- Charleston/Kanawha County, WV: information page in phone directory.
- Louisville/Jefferson County, KY: brochure
- Bucks County, PA: brochure
- Oak Ridge National Laboratory: technical report
- Contra Costa County, CA: brochure
- Tooele County, UT: information on 1996 Emergency Preparedness Calendar
- Pont-de-Claix, France: brochure

The steps in each of these procedures are listed in Appendix A and are summarized in Table 2.

3.3.1 Methods Specified in Published Instructions for Sheltering.

Apparently, most of the sheltering instructions published in the U.S. are based upon those presented in technical reports by the NICS[3] and ORNL.[1] There are significant differences among them, however, as Table 2 shows. Only three steps are common to all 11 procedures reviewed, and these three are the steps that constitute normal sheltering in place: closing windows and doors, turning off HVAC, and staying indoors while listening to radio or television for instructions.

The omission of some steps may reflect an effort to simplify the instructions so that they can be understood and performed easily by the average person. Doing so, however, implies judgements on the value of those steps omitted. The following is a brief discussion of some of the measures specified in the published procedures. Some are addressed because of their importance, others because they are of questionable benefit for protection against a potential release chemical warfare agents.

Table 2. Summary of Measures Specified in Published Guides or Reports on Sheltering

Measures Common to All

- Close all windows and doors.
- Turn off all fans, heating, and air conditioning systems.
- Stay in the room and listen to radio or TV until told to evacuate.

Sealing Measures Found in Some

- Place wet towels in the cracks under the doors. [a,c,g,h,i]
- Close the fireplace damper.[a,b,e,f,i,k]
- Tape plastic (such as drop cloths) over windows.[h]
- Tape outlets or electrical fixtures. [g,h]
- Tape around doors, windows, exhaust fans or vents.[a,h] Cover cracks with tape.[c]
- Use the plastic garbage bags to cover windows, outlets, and heat registers.[a]
- Block out all outside air.[d]
- Lock windows (they seal better when locked).[f,h,i,k]
- Close as many internal doors as possible in the home or building.[f,g,j,k]
- Use tape and plastic food wrapping, wax paper, or aluminum wrap to seal bathroom exhaust and grilles, range vents, dryer vents, and other openings to the outdoors.[f,i]
- Seal plumbing and cabinets.[g]
- Switch inlets to closed position, seal gaps around window air conditioners with tape and plastic sheeting, wax paper, aluminum wrap.[f] Seal all gaps with plastic sheeting or wrap.[k]

Room Selection Criteria Found in Some

- Use an above ground room (not the basement).[a,k]
- Select an interior room, no or few windows, no plumbing fixtures if possible, no window air conditioners, and at least 10 sq ft floor area per person.[g]
- Use leeward area of basement and seal cracks and openings for extra protection (Do not use basements if toxic gases are heavier than air).[e]
- Preferably use a room with no or few windows.[a,c]
- Use a room away from the factory (source)[j]. Use a central room.[k]

Complementary Protective Measures Found in Some

- In some cases, cover your mouth and nose with a damp cloth.[a,b,c,e,f,i,j]
- In the bathroom, close door, turn on the shower in a strong spray to "wash" the air.[f]
- Take frequent shallow breaths and stay calm.[b] Remain calm, relax, and stay immobile.[g,j]
- Don protective clothing to vacate shelter.[g]
- If you feel a prickling sensation on exposed skin, wash with water.[j]

Measures for Minimizing Induced Leakage Found in Some

- Minimize the use of elevators.[f,k]
- Ensure all ventilation systems are set to 100% recirculation.[f] Use recirculated air only.[k]

Measures to Ventilate After Cloud Passing Found in Some

- At the "all clear" open windows and doors, ventilate the building, and go outside.[c,e,g,h,j]

Other Measures Found in Some

- Keep the phone lines open for official use.[b,d,i]
- Have a kit of supplies (radio, flashlight, food, water, medicines, duct tape)[a,e,g,h]
- Have a ladder, stool, or chair, available.[g]
- Keep your pets inside [c,f,i,k]
- If danger of explosion, close curtains, window shades, blinds; stay clear of windows.[a,f]

a - American Red Cross; b - The City of Deer Park, TX; c - Charleston, Kanawha County, WV;
d - Louisville/Jefferson County, KY; e - Michigan State Police; f - Bucks County, PA.; g - ORNL Technical Report;
h - National Institute of Chemical Studies; i - Contra Costa County, CA. j - Poin-de-Claix, France. k - Tooele, UT.

3.3.1.1 **Turning off HVAC Systems.**

Turning off all HVAC systems is critically important, whether these are recirculating or ventilating, central or window-type systems (although two sets of instructions listed in Table 2 inappropriately state that the recirculation fan can be left on). The HVAC affects the protection afforded by sheltering in three ways. First, turning off the central/ recirculation fan reduces the induced leakage as discussed in Section 3.2.1.2. Second, if a furnace or stove which draws combustion air from the living area is in use, turning it off eliminates the infiltration induced by combustion. Third, if sheltering takes place during the heating or air conditioning season, turning off the HVAC will reduce the difference in indoor and outdoor temperatures and consequently the infiltration caused by the stack effect. This last effect would not likely to be as great as the other two in sheltering situations, because changes in building temperature would occur slowly and thus be small in magnitude over the period in which sheltering would likely take place.

3.3.1.2 **Selecting and Sealing a Room for Sheltering.**

Expedient sealing measures and room selection criteria in procedures published by the NICS[3] and ORNL[1] are based upon data from energy conservation studies regarding the most common pathways of infiltration. Such data show a wide range in the relative component leakage, as would be expected with the variations that exist in construction practices, building design, and the configuration of components.

One study of Texas houses showed the six areas of largest air leakage to be the sole plate (junction of walls and floor, behind the baseboard), accounting for 24.6% of the leakage; electrical wall outlets, 20.3%; air conditioning ducts, 13.5%, exterior windows, 11.8%; fireplace with damper closed, 5.5%; range vent (dampered), 5.2%.[25]

In another study, an analysis of 19 houses with fireplaces, a different distribution of leakage was found: sill and wall/ceiling joints, 31%; HVAC systems, 15%; fireplace, 14%; pipes, 13%; doors, 11%; windows, 10%; vents, 4%; and electrical outlets, 2%.[26]

The two studies have very dissimilar values for electrical outlets but show the other major pathways to be of the same relative magnitude: sole plate or sill plate, HVAC systems, fireplace, pipe penetrations, windows, doors, and vents. Ideally, the room selected for sheltering should have as few of these pathways as possible, and sealing measures should be focused upon the areas of the greatest leakage potential to produce the largest reductions in air exchange rate in the least time.

Most published procedures reviewed for this report do not, however, address these leakage pathways, either with expedient sealing techniques or room selection criteria. Selection criteria related to leakage appear in only three of the published procedures. Even the simplest measure of placing a wet towel at the base of the door appears in only half the procedures. Other expedient techniques for reducing infiltration are omitted from most: Closing the fireplace damper is addressed in five, taping vents in four, taping windows in three, taping electrical outlets in two, and taping plumbing penetrations in one. Measures to reduce leakage through the two major pathways--the sole plate/ sill plate and HVAC ducts--are not specified in any of the procedures reviewed.

Leakage through the sole plate occurs because wallboard does not usually extend to the subfloor and thus is not sealed to the sole plate or subfloor. This allows air to pass under the wall from behind the baseboard trim. The technique for reducing air leakage at the sole plate is to remove the baseboard temporarily and cement a 3-inch wide strip of fiberglass along the wall-to-floor joint. A similar path of infiltration is along the sill plate, which rests atop the concrete foundation wall. In retrofitting a home, leakage through this interface is reduced by caulking.

To reduce leakage through the HVAC ducts external to the living area, one must enter the attic or crawlspace and apply tape to the joints of the ducts. None of these three procedures can be considered expedient measures; however, they are among those techniques to be applied for what is described as enhanced sheltering.

The ideal room for sheltering is one which has no outside walls, no windows, no vents, one door, lighting and electrical outlet for radio or television, and adequate room for the expected number of occupants. Such a room does not exist in most houses. In a typical dwelling, the only rooms that may have no outside walls and no windows are bathrooms and walk-in closets. However, building codes require that a bathroom must have a ventilation fan if it has no window.

There are two other selection criteria found among the published procedures: that the room should be on the leeward side of the building and that it should not be in the basement. The former is desirable in that the interior concentration on the leeward side will lag that of the windward side. Avoiding use of the basement assumes that the agents will eventually settle into the lowest point of the house, the basement. Anecdotal data on mustard attacks of World War I indicate that this would occur.[20] A report by the NICS[3] indicates that there is no advantage to sheltering in upper floors because of differences in air exchange rates between the two floors. However, as is noted in Section 3.2.1.2, there are data showing that the second floor would be preferable to the first floor because the air exchange rate is likely to be lower on the second floor.

Room selection criteria developed by ORNL are summarized in Table 3.

Table 3. Room Selection Criteria Developed by ORNL[1]

- At least 10 sq ft per person
- Relatively small, with no outside walls, on ground floor
  or, if not available, a small room with no windows
  or, if not available, room with smallest number of windows and doors
- Avoid rooms with window air conditioners, windows that leak, vents to outside (such as automatic dryer vents and circulation vents).
- Avoid rooms with exhaust vents that automatically start when the light is turned on.
  If all these elements are the same for two rooms, chose the room that is free of plumbing fixtures.

This table presents some of the criteria in order of importance; however, because rooms in a typical dwelling are not likely to fit this or other criteria easily, room selection would appear to be a process too complex for the average person to perform correctly.

3.3.1.3 Placing a Wet Rag over Nose and Mouth.

This complementary protective action, which appears in 7 of the 11 procedures, is essentially the same expedient employed by soldiers caught in the first chemical attack of modern warfare, a chlorine release in 1915. Experiments at Fort Detrick, MD, have shown that a handkerchief folded to eight layers or a bath towel folded to two layers can reduce the inhalation of aerosol by 85 to 90% whether the cloth is wet or dry.[27] However, this would have only a small effect against gases that hydrolyze well (such as chlorine or phosgene) and virtually no effect against the chemical agents in the U.S. stockpile. (Mr. Robert Morrison, ERDEC Research and Technology Directorate, personal communication).

3.3.1.4 Turning on the Shower.

Another complementary action, turning on the shower appears in one of the published sheltering procedures. With the shelter established in a bathroom, there are two effects that can be achieved by turning on the shower. Running the shower with a closed drain creates a small outward flow of air by displacing the air in the room at the volumetric flow rate of the water. Secondly, the small water droplets have a scrubbing effect and can remove airborne contaminants from an enclosure, as was shown in research conducted by the Army[28,29] and Navy.[30] Similar to a process used for odor control in industrial applications, it involves spraying water droplets of about 100 to 200 micron diameter into the enclosure. The droplets, which present a large total surface area, absorb the vapor and carry it from the air as they slowly settle. The benefit of these two effects has not been quantified for an application such as sheltering in place.

3.3.1.5 Potential Measures Not Included in Current Instructions.

A household vacuum cleaner has been tested as an expedient filter unit to remove airborne particles when sheltering against radiological hazards.[9] Filtering chemical vapors requires an adsorption medium not usually found in households; however, indoor air purifiers that contain a carbon filter medium in addition to a high efficiency particulate air (HEPA) filter are now becoming widely available to consumers. These do not have the sorptive capacity or efficiency of standard carbon filters used in protective equipment, but they offer potential for significantly increasing the protection provided by a safe room in sheltering in place. These are recirculation type units; they filter the air within an enclosure and cannot be applied to establish a pressurized shelter. Similarly, furnace filters that contain a carbon filter medium are now available to consumers. These provide the capability to scavenge chemical vapors when the central HVAC fan is operating. Because of the adverse effects of HVAC operation during sheltering, however, carbon furnace filters should be considered for use in purging the building only after the hazardous plume has passed.